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Operationalizing sustainability in urban coastal systems: A system dynamics analysis

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ABSTRACT

We propose a system dynamics approach for Ecologically Sustainable Development (ESD) in urban coastal systems. A systematic analysis based on theoretical considerations, policy analysis and experts' knowledge is followed in order to define the concept of ESD. The principles underlying ESD feed the development of a System Dynamics Model (SDM) that connects the pollutant loads produced by urban systems' socioeconomic activities with the ecological condition of the coastal ecosystem that it is delineated in operational terms through key biological elements defined by the EU Water Framework Directive. The receiving waters of the Athens Metropolitan area, which bears the elements of typical high population density Mediterranean coastal city but which currently has also new dynamics induced by the ongoing financial crisis, are used as an experimental system for testing a system dynamics approach to apply the concept of ESD. Systems' thinking is employed to represent the complex relationships among the components of the system. Interconnections and dependencies that determine the potentials for achieving ESD are revealed. The proposed system dynamics analysis can facilitate decision makers to define paths of development that comply with the principles of ESD.

1. Introduction

Human systems are strongly interrelated with coastal ecosystems. Various human activities (e.g. wastewater discharging, over fishing) affect the water quality of coastal ecosystems, while the goods and services provided by the coastal ecosystem are essential for the economic process and human well-being (e.g. fisheries, recreation). When it comes to urban systems, the interactions between human activities and coastal systems are more intensified due to the increase in population density and associated economic activities. For example, the high urbanization rates in the Mediterranean coastal countries along with the lack of wastewater infrastructure in many coastal areas exacerbate the degradation of coastal waters (Diaz and Rosenberg, 2008; Iglesias et al., 2007; UNEP, 2008).

Systems' thinking facilitates the recognition that fundamental laws of physics are relevant to the economic processes as there is no way "to create something from nothing" or "to create nothing from something" (Farley, 2012; Georgescu-Roegen, 1971). System dynamics approaches have been used in the relevant literature to explore the interactions between human and coastal systems with respect to the sustainability

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prospects and especially the sustainable management of water resources (Chang et al., 2008; Hopkins et al., 2012; Mavrommati et al., 2013; Mirchi et al., 2012; Newton, 2012).The methodology of system dynamics traces the roots of the problem, and both qualitative and quantitative analyses can reveal the causes of unsustainable water resources management (Mirchi et al., 2012; Sterman, 2012). Studying the structure and processes underlying the relationships between the human and natural systems can enable decision makers to learn systems' responses under alternative scenarios of socio-ecological evolution and define sustainable paths of development. Systems thinking facilitates holistic considerations, without which may result in the adoption of ineffective and inefficient policies (Hopkins et al., 2012). Recently, the methodology of system dynamics has been also proposed for studying water and wastewater network management with respect to the prospects of financially self-sustaining water utility (Rehan et al., 2011).

The current paper proposes a framework of systems' analysis for Ecologically Sustainable Development (ESD) of urban systems in relation to the ecological condition of coastal ecosystems. The concept of ESD plays a key role as it determines the systems' parameters and structure that affect the decision making.

We built a System Dynamics Model (SDM) to quantify the effects of human activities of urban coastal cities on the ecological condition of the receiving waters. The model focuses on examining the impacts of pollutant loads from point sources on the ecological status of the receiving waters. The model adopts the environmental objective of Good Ecological Status (GES) as proposed by the Water Framework Directive (WFD) (Commission of the European Communities, 2000). To operationally assess the ecological status of coastal waters the "Ecological Evaluation Index" (EEI) has been applied (Orfanidis et al., 2001a, 2003; Panayotidis et al., 2004). Based on the EEI, the current study proposes a SDM for linking anthropogenic activities taking place in the Athens Metropolitan Area with the ecological status of the Inner Saronikos Gulf. GES is clearly connected to sustainability. The preservation of GES ensures the provision of the main ecosystem services to the urban population, such as fisheries, recreation, waste assimilation capacity and other cultural amenities. In addition, the concept of GES reflects an operational policy objective that is accepted by coastal experts within the context of interdisciplinary consideration of ESD (Mavrommati and Bithas, 2013; Mavrommati and Richardson, 2012). The methodological contribution of the paper is the integration of sub-models inspired by different disciplines (hydrology, biology, economics) into a simple and operational model that serves the aspirations of sustainability science and addressing the needs of decision makers.

2. Methods

2.1. *Defining ecologically sustainable development at the operational level*

Ecologically Sustainable Development (ESD) refers explicitly to the potentials of future generations. One of the major objectives of our research is not only to build a model that shows how human beings affect the ecological condition of coastal systems and vice-versa but to understand the consequences of socioeconomic activities of the current generation on those of the future. This objective is not feasible without understanding the principles of ESD at the operational level. In this line of thinking, a systematic process, based on sustainability literature, coastal experts' opinion and European environmental policy is followed to define ESD in coastal ecosystems. Then, we develop a SDM that captures the operational principles of ESD in coastal ecosystems and follows the general principles of sustainability science.

2.2. *Designing the System Dynamics Model*

With respect to the operational definition of ESD, our analysis includes the components of the urban and the ecological systems and captures the complexity of the coupled human and natural systems (Liu et al., 2007; Millennium Ecosystem Assessment, 2003; Stevenson, 2011). The model is designed to run 43 years (1987–2030) with a delta time (DT) equal to 0.25 years. This model is written in the STELLA software simulation language (version 9.1.4) and benefits from tools such as using table functions for representing nonlinear functions. The parameters used in the SDM and their numerical representation were defined through the relevant literature and interviews with experts in the field.

3. Defining the concept of ecologically sustainable development at operational level: lessons from sustainability science, policy and experts opinion

Designing for ecologically sustainable development constitutes one of the major challenges of our century as there is no consensus on the operational definition of ESD. This study follows a systematic process and defines the ESD based on three levels of analysis (Fig. 1).

3.1. *Sustainability science*

The concept of ESD has been extensively discussed in the literature by the sciences of economics and ecology but the two disciplines have generally worked separately (Ostrom and Cox, 2010). The prevailing ESD schools of thought are the scientific paradigms of strong and weak sustainability with main difference being the potentials of substitution between the natural and human made capital as well as the relationship between the socioeconomic and natural systems (Mavrommati and Richardson, 2012; Neumayer, 2010). The new field of sustainability science rejects the traditional separation of social and natural sciences and calls scientists to move beyond the methodological barriers of their particular discipline to better approach common research questions (Carpenter et al., 2009; Cummins and McKenna, 2010; Palmer et al., 2005). In this respect, finding the balance between human and natural systems requires the integration of the knowledge of social and natural sciences into a common framework of analysis and thinking (Cash et al., 2003). By understanding the mechanisms and processes underlying the

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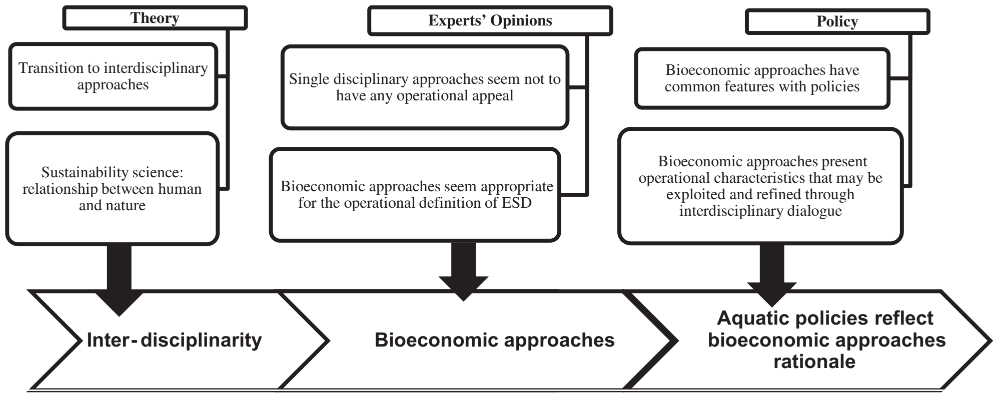

Fig. 1 – Operationalizing the concept of ecologically sustainable development: theory, experts' opinions and policy.

interactions between human and natural systems, achieving the objective of ESD is more feasible.

3.2. *Experts' opinion*

Interdisciplinary approaches, which incorporate the knowledge and findings of social and natural sciences, have been proposed as more appropriate compared to those based on single sciences (e.g. economics) for defining operational conditions of ESD in coastal ecosystems (Mavrommati and Richardson, 2012). Recent studies suggest that in accordance to the opinion of coastal experts, bioeconomic approaches such as Critical Natural Capital (CNC) and Biologically Crucial Levels (BCLs) which originate from socioeconomic sciences but adopt ecological or biological criteria for ESD, are more functionally and scientifically appropriate for maintaining the potentials of future generations to fulfill their needs and preferences (Bithas, 2008; Ekins and Simon, 2003; Ekins et al., 2003; Mavrommati and Richardson, 2012). The importance of integration with environmental and other studies is also an important field of sustainable research in economics for both environmental and ecological economists despite their opposing methodological roots (Illge and Schwarze, 2009).

3.3. *Policy for aquatic ecosystems*

The operational appeal of various representative ESD approaches at the policy making level shows that major policies for aquatic ecosystems share the same rationale and conditions as the bioeconomic approaches (Mavrommati and Bithas, 2013). In particular, the Water Framework Directive and the Clean Water Act adopt a framework for defining environmental objectives that considers the genuine knowledge from natural and social sciences. Environmental objectives are defined with respect to the preservation of biological functions and processes. At the same time, socioeconomic considerations such as public participation and cost-benefit analysis are incorporated into an integrated framework of decision making.

3.4. *Sustainable cities*

A city could be seen as an ecosystem with specific properties. Cities: (i) evolve with a specific structure in order to perform a very unique role in the socioeconomic process; (ii) are the leaders that drive society and economy toward the future; (iii) increase the efficiency of the realization of individual and social objectives (OECD, 1996) and; (iv) create novelty, new processes, and targets and patterns of evolution, by combining economic, social, cultural and demographic elements.

There are certain biological functions that are indispensable for the healthy ecological existence and evolution of urban systems. These functions are mainly defined with respect to the needs of human beings residing in urban systems. The provision of some indicative ecosystem services essential for human well-being such as clean air, recreation and drinking water should be ensured. These ecosystem services ultimately depend on the structure and functions of urban dynamics. The safeguarding of the crucial ecological functions within a certain geographical space is subject to the presence and interactions of key ecological elements bearing specific qualitative and quantitative features (Bithas and Christofakis, 2006).

3.5. *Defining the ecologically sustainable development operationally*

Our study defines the concept of ESD based on contemporary bioeconomic approach of Biologically Crucial Levels (BCLs) (Bithas, 2008; Bithas and Nikjamp, 2006). The starting point of the BCLs approach is the explicit equal weight of the welfare of future generations to the current (i.e., the discount rate tends to zero). The BCLs approach considers that the social and economic systems are subsystems of the ecological system implying that the maintenance of the functions and processes of natural systems constitutes a prerequisite for the existence and evolution of the socioeconomic processes.

Two distinct operational conditions for sustainable development are proposed by the BCLs approach (Bithas, 2008; Bithas and Nikjamp, 2006). The first condition, which is the "necessary" one, demands "the maintenance of the biologically and ecologically critical levels (BCLs) of environmental systems functions and processes that ensure the ecosystems' minimum biological–ecological integrity". The concept of BCLs extends to the so-called pollutants that should be reduced below those crucial levels (thresholds) that may disturb the ecological condition of ecosystems. As a result, the

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BCL approach adopts a biological constraint on the socioeconomic processes and development.

The second condition refers to the provision of natural inputs (mass and energy) to the productive sector of the economy. This provision should have a long-term perspective, taking systematically into account the potential needs of future generations. The use of natural resources as inputs to the production process should be governed by: avoidance of wasting non-renewable resources, limiting the use of renewable resources within their regeneration rate, and gradual substitution of non-renewable resources with renewable ones.

Our study focuses on the first operational condition (the preservation of BCLs) and the SDM model is designed with respect to this. The term biological sustainability is used to define the first condition toward ESD and for the purpose of our study is equalized with the objective of good ecological status as set by the WFD.

4. The System Dynamics Model

4.1. *Study area*

The Inner Saronikos Gulf is a coastal water body supporting the provision of ecosystem goods and services to the citizens and visitors of the capital of Greece, Athens (Fig. 2). The population of the Athens Metropolitan Area (AMA), according to the last census, is 3.8 million which account for the 35% percent of the total Greek population (Hellenic Statistical Authority, 2011). The rapid urbanization in the AMA after the 1950s was not accompanied with the appropriate infrastructure and policy for protecting the aquatic environment. Wastewater was discharged untreated into the shallow waters of Keratsini Bay and the Saronikos Gulf, resulting in one of the most polluted areas in the eastern Mediterranean until 1995, thus creating constraints for recreation, fishing and other uses of waters (Dassenakis et al., 2003; Scoullos et al., 2007).

The accession of Greece into the European Union (EU) in 1981 and its obligation to comply with EU laws created the appropriate conditions for managing water resources sustainably. For example, the compliance of the Greek law with the Directive 91/271/EEC imposed certain criteria for wastewater pollutant loads discharged to surface and coastal waters. The minimum required reductions in relation to the load of the influent for Biological Oxygen Demand (BOD_5) and Total Suspended Solids (TSS) are 70–90% and 90% respectively (Council of the European Communities, 1991). If urban wastewater treatment plants discharge to sensitive areas then additional reductions of total phosphorus and total nitrogen 70–80% are required (Council of the European Communities, 1991). During 1995, the operation of the Athens wastewater treatment plant (WWTP) of Athens on Psitalia Island started with a primary level of treatment and secondary treatment technology has been applied since 2004. The WWTP is designed with a maximum capacity of 1 million m^3 per day and cannot support the urban agglomeration above a certain level of population and economic activities ceteris paribus. Currently the average daily flow is 730,000 m^3.

4.2. *Problem articulation and dynamic hypothesis*

The ultimate goal of this paper is to use SDM: (i) to identify the interactions between the urban system and the ecological condition of the coastal system; and (ii) to define under which

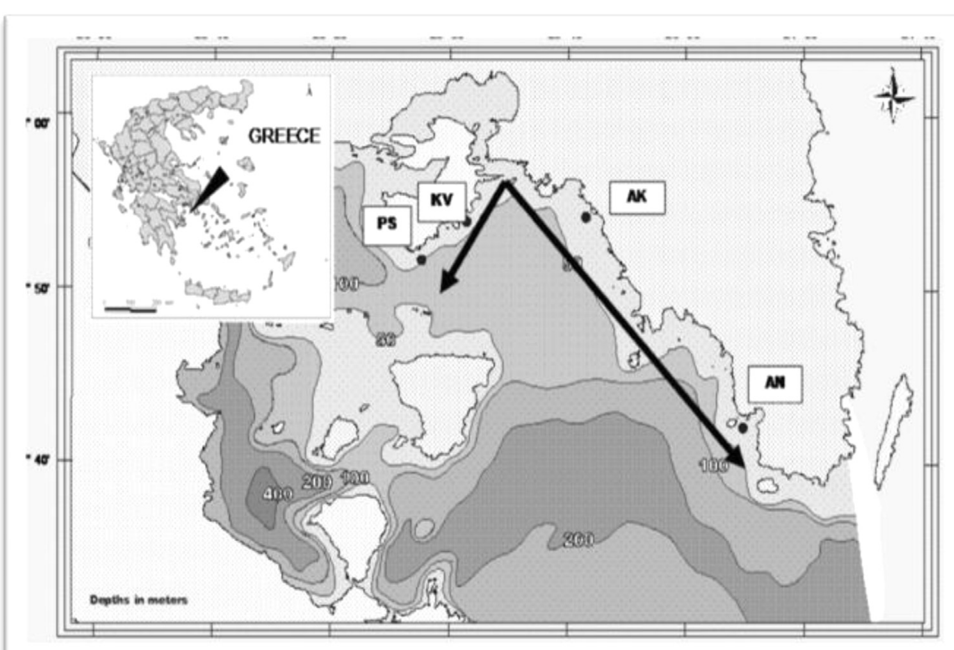

Fig. 2 – Map of the coastal system (Saronikos Gulf) receiving effluent from the Athens Metropolitan Area, Greece. Sampling sites for Saronikos Gulf macroalgae: PS = Peristeria, KV = Kaki Vigla, AK = Agios Kosmas, AN = Sounio.

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conditions ecologically sustainable development in the urban coastal system of the AMA is feasible. The study focuses on the impacts of the pollutant loads from the wastewater discharges on the ecological status of coastal waters.

The model is comprised of two systems: the urban and coastal systems. Fig. 3 is a casual loop diagram of our model that shows the feedback loops among the key parameters of the systems. Positive arrows (+) represent a change in the same direction, while negative arrows (−) indicate a change in the opposite direction (Ford, 1999). The general idea underlying our analysis is that the implementation of a policy and management framework facilitates change toward sustainable paths of development and can potentially limit the environmental pressures of human activities within the boundaries imposed by the adopted indicator of sustainability (Fig. 3a). A key parameter in the urban system is human population size as it drives the volume of wastewater discharges and produces point source pollutant loads (Fig. 3b). The impacts of

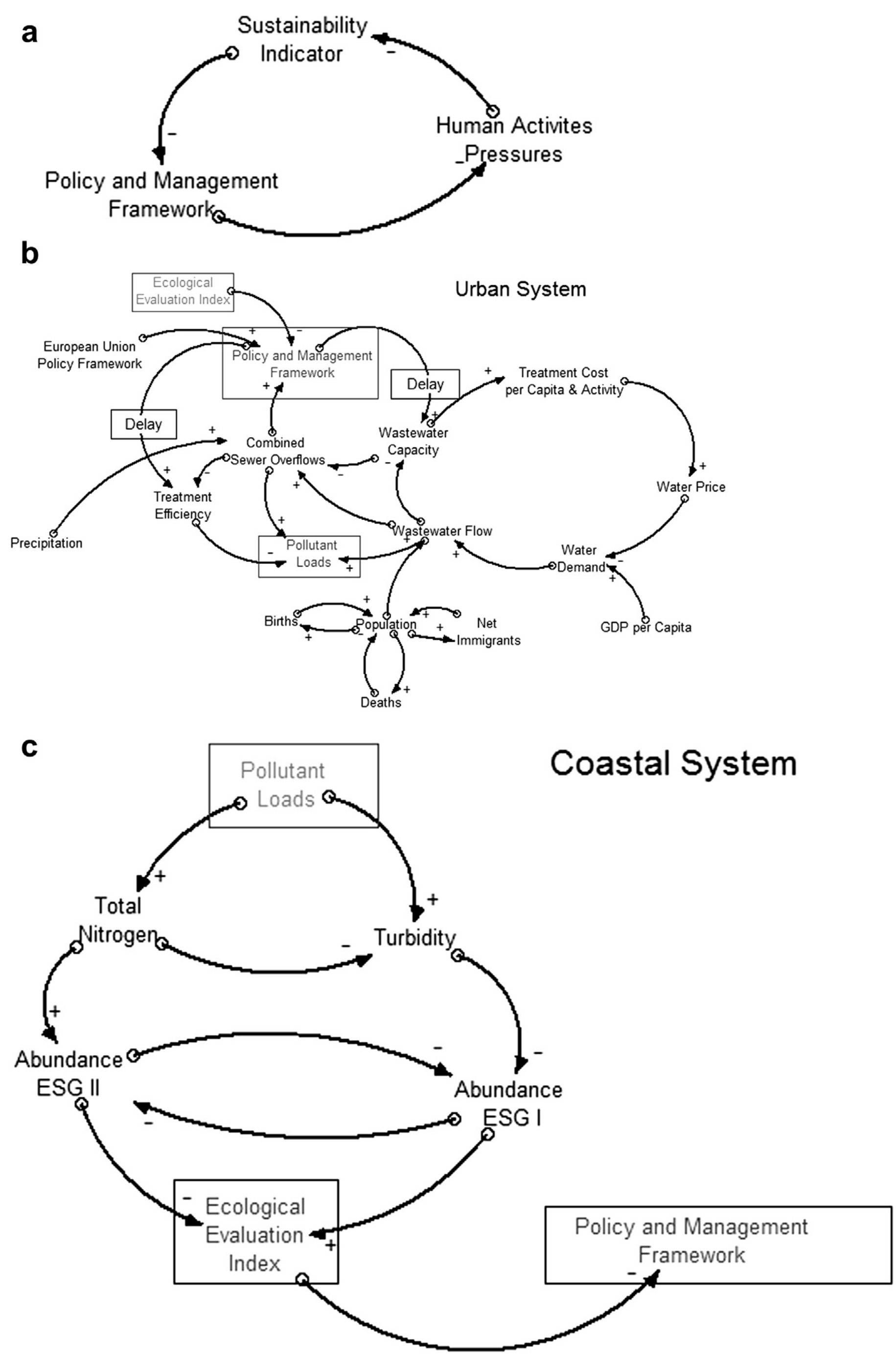

Fig. 3 – Casual Loop Diagram of the three main components of the interactions among the urban and coastal system in Athens Metropolitan Area with respect to sustainability (a) and further details in (b) and (c). Positive arrows (+) represent a change in the same direction. Negative arrows (−) represent a change in the opposite direction. The two systems are connected through pollutant loads (grey) and the ecological evaluation index (grey) that informs policy making (grey).

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discharged pollutants entering the coastal waters can be measured by the Ecological Evaluation Index (EEI). The EEI depends on relevant abundance of two groups of Macrophytes and feeds the policy and management framework. Low values of the EEI reveal the need for additional policy and management actions in order to achieve sustainability (Fig. 3c). In our case, the policies for coastal waters enforce a mechanism for reducing the WWTP outflow of pollutants loads which in turn improves the ecological quality of coastal waters. Table 1 shows the key model parameters and their values.

4.3. *Components of the urban system*

Urban coastal systems are contaminated by pollutants loads via point (e.g. municipal and industrial wastewater effluents) and non-point sources (e.g. industrial and urban runoff). A number of studies have investigated the impacts of pollutant loadings on the ecological condition of the Inner Saronikos Gulf (Costelloe and Nikolaidou, 2001; Friligos, 1985; Scoullos et al., 2007; Tsiamis et al., 2013). Our focus is on those factors determining (i) the wastewater volume and; (ii) the pollutant loads discharged to the Inner Saronikos Gulf.

4.3.1. *Wastewater volume determination*

Our model estimates the volume of wastewater based on water consumption and human population size. Data for each category of water consumption were collected from the Athens Water Supply and Sewerage Company (EYDAP SA) for 1987 to 2008 and suggest that water consumption depends mainly on residential water consumption and secondly on industrial and other categories of water consumption (non-residential water consumption) (Athens Water Supply and Sewerage Company, 2009) (Fig. 4). Based on these data, non-residential consumption, comprised of industrial, public and other uses, is represented as a fraction (24%) of the residential water consumption. The water consumption per capita function is specified on the basis of the relevant theory and data from the water authority in Greece (Dalhuisen et al., 2003; Germanopoulos, 1990; Kallis, 2010; Karka et al., 2011; Polycarpou and Zachariadis, 2013).

Decision makers need to know the trends of water consumption and wastewater discharges in order to plan better for the society's future needs. It is also assumed that 20% of consumed water is not converted into wastewater as it is being lost for various reasons such as garden irrigation, drinking water and network losses (Karka et al., 2011). Given that part of the sewerage system in many cities may be combined (as the case of the AMA), the carrying capacity of wastewater treatment plant is crucial for managing overflows. Managing overflows, apart from the environmental costs, involves high operational and investment costs. Although some cities are financially able to reduce overflows by upgrading or replacing the existing aging infrastructure and can cover this cost through increased sewer rates, this is not feasible for economic vulnerable cities (Tibbetts, 2005).

Table 1 – Description of key parameters in the urban and coastal systems of the Athens Metropolitan Area, Greece.

Parameter	Initial value	Unit	Data source
Population	3,469,976	People	Hellenic Statistical Authority (2009)
Births	Depends on the crude birth rate	People/year	
Deaths	Depends on the crude death rate	People/year	
Net Migration	Depends on the crude net migration rate	People/year	
Per Capita Water Demand	Endogenous parameter	m^3/day/people	Athens Water Supply and Sewerage Company (2009)
Real Mean Water Price		€/m^3	Athens Water Supply and Sewarage Company (2010a)
Treatment cost per capita & activity		€/m^3	Athens Water Supply and Sewarage Company (2010a)
Wastewater Capacity	Initial value is 0	m^3	
Combined Sewer Overflows	Endogenous parameter. Depends on the volume of wastewater and wastewater capacity	m^3/day	
Per Capita GDP		€/year	Hellenic Statistical Authority (2010)
Policy and Management Framework	Endogenous parameter described by a function depending on the sustainability indicator. Initial value is 0 and maximum value is 1.	Policy	
Wastewater flow	Endogenous. Equation??	m^3/day	Athens Water Supply and Sewerage Company (2008)
Pollutant Loads (Biological Oxygen Demand and Total Suspended Solids)	Pollutant loads described through Eq. (6).	(mg/l)/day	
Precipitation		m^3/day	Hellenic National Meteorological Service (2011)
Treatment Efficiency	Depends on the Policy framework and combined sewer overflows.	% removal	Athens Water Supply and Sewerage Company (2008)
European Union Framework	Exogenous parameter. It takes value 1 after 1991.	Policy	
Total Nitrogen	Initial value 3.033	mg/l	Panayiotidis (2009)
Turbidity	Initial value 11	secchi m	
Ecological Status Group I	Initial value 5	% abundance/400 cm^2	
Ecological Status Group I	Initial value 25	% abundance/400 cm^2	
Ecological Evaluation Index	Endogenous. Defined through the matrix in Fig. 6	Ecological status	

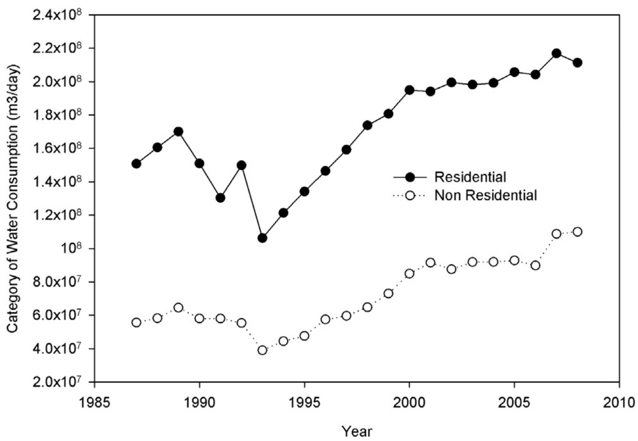

Fig. 4 – Residential and Non-residential Water Consumption in Athens (1987–2008).

For the purpose of our model, we use a log–log per capita water demand function. Based on the available data (Athens Water Supply and Sewerage Company, 2009), the residential water consumption in the AMA is described according to Eq. (1):

$$q_w = 0.694^1 - 0.231 * p + 0.443 * \text{GDP} \quad (1)$$

$R^2 = 0.798$

Std. Error of the Estimate = 0.082

The dependent variable is the log of daily per capita water demand (*q*), while the weighted average price (*p*) and per capita Gross Domestic Product (GDP) constitute the independent variables. Water price and GDP are expressed in real terms using the Consumer Price Index (CPI) as the deflator. The price elasticity indicates that a 1% price increase will reduce demand by 0.231% with all else equal. The income elasticity is high indicating that a 1% increase in income will result in an increase of demand by 0.443 with all else equal. Those estimations are in line with the relevant literature worldwide (Dalhuisen et al., 2003; Polycarpou and Zachariadis, 2013). Apart from price and income, other variables may affect the per capita water demand such as precipitation, lifestyle, temperature, drought periods etc. The equations for estimating the volume of wastewater are expressed as following:

$$\text{Wastewater Flow} = \text{Residential Flow} + \text{Nonresidential Flow} + \text{Inflow Urban Runoff} \quad (2)$$

$$\text{Residential Flow} = 0.8 * \text{Population} * \text{Per capita water demand} \quad (3)$$

[1] Where $e^{-6.323} = 0.694$. In the model, the equation had anti-logarithm form.

$$\text{Nonresidential Flow} = 0.24 * \text{Population} * \text{Per capita water demand} \quad (4)$$

$$\text{Urban Runoff} = F(\text{precipitation}), F(0) = 0 \quad (5)$$

In our model, we assume that urban surface runoff affects the volume of wastewater and the relevant pollutant loads as during periods of heavy rainfall, the combined wastewater can exceed the capacity of wastewater treatment plants. Sustainable storm-water management is necessary for maintaining healthy ecological functioning of urban coastal waters (Barbosa et al., 2012). Recent study suggests that although the volume of urban runoff is less than 10% of the catchment area, it affects both the quantity and quality of the effluent received in the WWTP (Karka et al., 2011). The estimation of this parameter is based on methods and assumptions designed specifically for Greek cities and calibrated for the city of Athens (Zalachori et al., 2008). We compared the inflow of wastewater for dry and wet weather for the months that the per capita water demand does not have significant differences (Table 2).

Based on Table 2, we estimated a graphical function representing for the relationship between the level of precipitation and the additional flow entering the combined sewer system (Fig. 5).

4.3.2. *Pollutant loads*

The concentrations of pollutant loads of residential and non-residential wastewater disposal among other parameters depend on the volume of wastewater disposal (pollutant load per use), lifestyle and the level of treatment (Kato, 2005). Our data, similarly to other studies, suggest that the relationship between the volume of wastewater and pollutants concentrations is not linear (Karka et al., 2011). The biological oxygen demand (BOD_5),total suspended solids (TSS) and total nitrogen (TN) are the major pollutant loads that affect the ecological condition of Athens receiving waters. The model involves three periods of wastewater treatment technology between 1987 and the present. In the first period (1987–1995), the wastewater is pretreated and treatment efficiency is zero. In the second period (1995–2004), after the operation of the primary WWTP of Athens in Psitalia, approximately 35% of the incoming BOD_5 and 60% of the TSS are removed (treatment

Table 2 – Comparison between the wastewater in flow into the Wastewater Treatment Plant for dry (June) and wet (January) months from 2003 to 2007. Data were obtained from Athens Water Supply and Sewerage Company (2009) and Hellenic National Meteorological Service (2011).

Year	Dry period inflow (m^3)	Wet period inflow (m^3)	Precipitation dry period (mm)	Precipitation wet period (mm)
2003	724,810	788,083	0.0	52.9
2004	695,273	905,500	0.4	144.6
2005	646,379	771,613	1.7	86.9
2006	798,200	822,828	20.9	64.3
2007	775,567	761,548	7.5	0.5

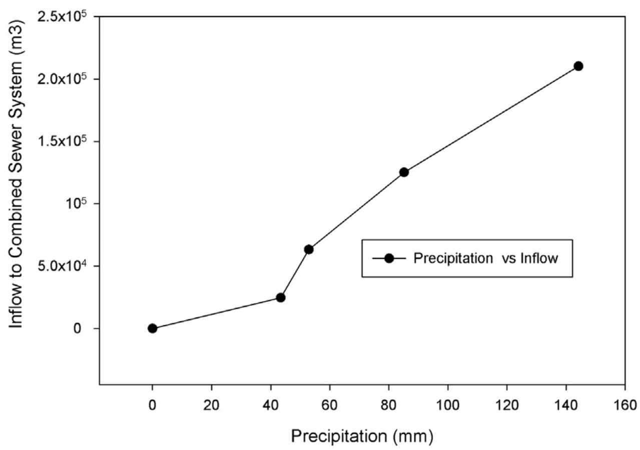

Fig. 5 – The relationship between precipitation and the resultant inflow into the combined sewer system.

efficiency is 35% and 60% for BOD_5 and TSS respectively). In the last period (2004-present), the secondary treatment removes 90% of the BOD_5 and TSS presented in the inflow of wastewater (treatment efficiency is 90% for BOD_5 and TSS). In our model pollutant loads discharged in the receiving waters are estimated through the wastewater volume and treatment efficiency. Treatment efficiency is defined as the percent of pollutant loads removed after treating the wastewater.

The equation describing pollutant loads outflow is as follows:

$$\text{Pollutant Load Outflow} = \text{Pollutant Load Inflow} * (1 - \text{treatment efficiency}) \quad (6)$$

where Pollutant Load Outflow stands for the outflows of BOD_5 and TSS. The wastewater treatment efficiency depends on the existing policy and management framework. We base our analysis on the simplified assumption that an exogenous parameter, i.e., the European Union Policy Framework, has a positive effect at the current environmental policy. Further research is needed to better understand the process by which European policy determine the management framework.

Sewer rates increase to cover the cost of "treatment efficiency". In our case sewer rate is based on water consumption and has been increased by a total 40% since the operation of the AMA WWTP (Athens Water Supply and Sewarage Company, 2010a,b).

4.4. *Components of the ecological system*

The ecological subsystem describes the ecological condition of the Inner Saronic Gulf. For describing the ecological condition of coastal waters, the objective of Ecological Status (GES) defined through the WFD is used. The definition of GES (Annex V, WFD) explicitly spells out the key role that biological quality elements play in the structure and function of ecosystems and provides the appropriate legislative framework for protection of ecosystem services contributing to human well-being (Mavrommati and Bithas, 2013). In this context, the concept of GES is used to describe the objective of biological sustainability proposed by the BCLs approach.

Among other biological quality elements (BQE's) for the evaluation of the ecological quality status of marine coastal waters the WFD includes the marine benthic macrophytes and macroalgae. The other BQE's are the macroinvertebrates and the phytoplankton. The GES in a given area is reached when all the BQE's are at least at the "good" quality status class. Based on marine benthic macrophytes the Ecological Evaluation Index (EEI) has been developed (Orfanidis et al., 2001a, 2003; Panayotidis et al., 2004). According to EEI, marine benthic macrophytes are classified into two groups, the Ecological Status Group I (ESG I, late successionals) and Ecological Status Group II (ESG II, opportunistic) and the ecological status of coastal waters is determined based on their relative abundance (%), (Fig. 6, Orfanidis et al., 2003).

The EEI takes a numeric value ranging from 0.2 (bad ecological status) to 1 (high ecological status). In order to maintain the healthy function of ecosystems, the numeric value of EEI should be at least equal to 0.6 that corresponds to GES. Human systems should modify their activities within the boundaries imposed by the EEI (Fig. 3).

The main assumption underlying the building of the relationships of the ecological system is that the ESG I and II compete for the benthic space. Pollutant loads from the socioeconomic system affect the concentration levels of the stocks of TN- Total Nitrogen and Turbidity (Secchi, m), and consequently change the abundance of ESG I and II. The model is based on a two species colonization model (Chang et al., 2008; Hannon and Ruth, 1997).

5. Verification of SDM: behavior reproduction tests

The ability of SDM to reproduce the behavior of key parameters is tested through three common statistical metrics, the coefficient of determination (R^2), the mean absolute error (MAE) and the root mean square error (RMSE) and one less common statistical metric, Theil's Inequality Statistics (Table 3). Historical numerical data were used for assessing model fit to six key parameters in the model: population, per capita water demand, volume of wastewater, Biological

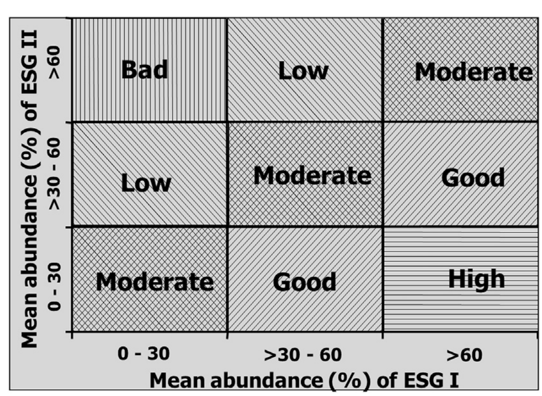

Fig. 6 – A matrix based on the mean abundance (%) of Ecological Status Groups to determine the ecological status of transitional and coastal waters (reproduced from Orfanidis et al., 2003).

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Table 3 – Behavior reproduction tests of a System Dynamics Model for the urban coastal system of the Athens Metropolitan Area, Greece.

Parameter	Metric						
	Years of historical data	R^2	MAE	RMSE	Theils inequality statistics ($U_M + U_S + U_C = 1$)		Data sources
Population	1987–2008	0.99	277.6	9100	U^M	0.097094482	Hellenic Statistical Authority (2009)
					U^S	0.0023694	
					U^C	0.9	
Per Capita Water Demand	1987–2008	0.95	0.02	0.026	U^M	0	Athens Water Supply and Sewerage Company (2009)
					U^S	0.999558863	
					U^C	0.000441137	
Volume of wastewater (WWflow)	2003–2007	0.6	32618.62	45,367	U^M	0	Athens Water Supply and Sewerage Company (2008)
					U^S	0.12945501	
					U^C	0.87048719	
Biological Oxygen Demand Outflow (BODOUT)	2003–2007	0.904	26.445	102.058	U^M	0.0000931	
					U^S	0.0254861	
					U^C	0.9744208	
Total Suspended Solids Outflow (TSSOUT)	2003–2007	0.962	18.2	65.148	U^M	0.051	
					U^S	0.064	
					U^C	0.885	
Ecological Evaluation Index (EEI)	1997–2007	0.974	0.024	0.0006	U^M	0.0132	Orfanidis et al. (2001a,b, 2003), Panayiotidis (2009), Panayotidis et al. (2004), Tsiamis et al. (2013)
					U^S	0.0133	
					U^C	0.9735	

Oxygen Demand Outflow, Total Suspended Solids Outflow and Ecological Evaluation Index (Athens Water Supply and Sewerage Company, 2008, 2009; Hellenic Statistical Authority, 2009; Orfanidis et al., 2001a; Orfanidis et al., 2003; Orfanidis et al., 2001b; Panayiotidis, 2009; Panayotidis et al., 2004; Tsiamis et al., 2013).

Theil's Inequality Statistics provide an elegant decomposition of the total error in the model. In particular, the Theil's statistics divides mean square error into three parts: bias, unequal variations, and unequal covariation (Sterman, 2000). Bias (U^M) indicates a systematic difference between the model output and data. Unequal variation (U^S) arises when the variances of the model and data differ. Unequal covariation (U^C) captures imperfect correlation between the model and data. When U^S or U^M are high, then questions about the assumptions of the model arise. Based on Table 3, U^S is high for the parameter per capita water demand. This is because the trend between model and data differ due to monthly variations of per capita water demand. Capturing the monthly variation of water demand is out of the scope of this model and for this reason this type of error does not compromise the models' usefulness.

Behavioral mode sensitivity analysis was also conducted to better assess models' robustness. Table 4 shows the ranges of some influential parameters that we tested. The model exhibits the same pattern of behavior irrespective of the parameters values implying that the basic structure is valid.

6. Results and discussion

The model provides dynamics underlying the components of the system during a period of 43 years (1987 to 2030). The starting year of 1987 was chosen to show the importance a policy framework (European Union Laws) in order to create the appropriate conditions that foster sustainability. This choice is also encouraged from the availability of data beginning this year. The model is appropriate for understanding the dynamics of an urban coastal system by examining reasonable long-term trends of systems' elements under alternative scenarios. With respect to sustainability, scenarios are defined as "coherent and plausible stories, told in words and numbers, about the possible co-evolutionary pathways of combined human and environmental systems" (Swart et al., 2004). Our model is not proposed for precise quantification but instead to reveal trends, interrelationships, limits and constraints in urban coastal systems. As a result, along with advanced hydrological and ecological models, the model can be used, to better understand the likely outcome of humans' actions.

Below, four alternative scenarios are presented indicating two main categories of evolution: natural and socioeconomic (Table 5). Natural evolutions occur through exogenous parameters such as an increase of rainfall intensity that might occur due to climate change (Giorgi and Lionello, 2008) (Scenario 2). Socioeconomic evolutions are mainly endogenous in the system inducing changes such as the volume of

Table 4 – Ranges of key parameters used for sensitivity analysis.

Parameter	Model value	Range
Rate of non-residential water demand	25%	10–35% (m^3/day)
Rate of water loss	20%	10–30% (m^3/day)
Average time for policy implementation due to changes in EEI	3 years	1–7 years (policy/year)
Rate of biological oxygen demand inflow	0.000521	0.0002–0.0008 ((mg/l)/m^3)
Rate of total suspended solids inflow	0.000497	0.002–0.0008 ((mg/l)/m^3)

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Table 5 – Scenario analysis of alternative socioeconomic and natural evolutions.

Scenario	Changing parameter(s)	Achievement of sustainability conditions (GES)	Source of the problem
S1	None (baseline scenario)	YES	None
S2	Combined sewer overflows: increase of storm-water flow (Urban runoff)	NO	Exogenous-climate change – increase of precipitation intensity
S3	Growth scenario	Likely	Endogenous-pollutant loads rate increase due to industrial growth
S4	Changes in preferences for water demand	After 2027 the objective of GES is not feasible	Exogenous-Income elasticity and industrial growth

wastewater or/and pollutant loads concentrations due to changes in the human population size, industrial activities or citizens' preferences (Scenario 1, 3 and 4). For each scenario Table 5 summarizes the changing parameter(s), the resulted outcome in terms of the ecological status of waters and the source of the problem.

Three graphs are presented for each scenario. The first graph describes the pollutants loads Biological Oxygen Demand Outflow (BODOUT), Total Suspended Solids Outflow (SSOUT) and the volume of wastewater (WWflow). The second and third graph present the ecological condition of the coastal ecosystem based on the abundance of macrophytes (ESG I and ESG II) and the ecological evaluation index (EEI) in relation to the sustainability indicator (BCL = 0.6). Seasonal variations in per capita water demand and the yearly cycle of the macrophytes are responsible for the fluctuations in the graphs. Per capita water demand fluctuates during the year reflecting the seasonal variation. The abundance of ESG I and ESG II have a yearly cycle and for this reason both have annual minimum and maximum value.

6.1. *The baseline scenario (S1)*

The baseline scenario assumes that the exogenous parameters of the model continue to reflect the past behavior. From 1987 until 1995, the lack of wastewater treatment results in the bad ecological quality of the Inner Saronikos Gulf. The benefits of the WWTP operation can be seen after the operation of the treatment plant in terms of pollutant reduction (30%) but in ecological terms are observable only after the secondary treatment of pollutants (95%) (Fig. 7). Since 2007, the average value of the EEI is above the biological crucial level of 0.6 reflecting the good ecological status of coastal waters. Under the current conditions, the achievement of the environmental objective of GES set by the WFD and compliance with sustainable paths of development seems achievable. This scenario assumes that excessive demand for wastewater capacity will be covered through citizens' payments for wastewater treatment and real per capita GDP will not be reduced more than the 2012 level.

6.2. *Combined sewer overflows (S2)*

The construction and operation of a WWTP does not secure the achievement of GES even if the population and the structure of socioeconomic activities remain the same. Climatological parameters (increased rainfall intensity due to climate change) or unexpected events (e.g. oil spills) can provoke deviation of GES. This scenario adopts the same assumptions of scenario 1 with the exception that the volume of storm-water flow considerably increases after 2021. We assume that the WWTP carrying capacity exceeds due to the increase of urban runoff (combined sewer overflows). As a result, the excess wastewater is discharged untreated to the receiving waters of the Inner Saronikos Gulf and increases the pollutant loads concentration (Fig. 8). This scenario shows that the achievement of desirable environmental objectives is subject to (un)expected conditions that can be potentially managed through adaptive measures such as replacing combined sewer overflows. The main constrain for employing adaptation measures is the induced cost for the citizens. An increase of rainfall intensity due to climate change is anticipated especially in the Mediterranean countries (Goldstein et al., 2012; Intergovernmental Panel on Climate Change, 2001).

6.3. *Growth scenario (S3)*

This scenario assumes that there will be an increase of the per capita GDP after 2019 (4% per year) with a subsequent increase in total residential and non-residential water consumption, resulting in an increase of industrial pollutant loads after 2015. We also assume an increase of water prices in order to cover the required cost for the additional wastewater capacity. These changes lead to an increase in pollutant loads that affect the ecological quality of the Saronikos Gulf. Although the change in the outflow of the pollutant loads appears slight, the growth rates of macrophytes are affected resulting in the increase of the relevant abundance of ESG II and corresponding decrease of the relevant abundance of ESG I. The objective of GES is marginally achieved (Fig. 9).

6.4. *Increasing water demand scenario (S4)*

In addition to the assumptions followed in the growth scenario, the income elasticity increases from 0.44 to 0.5 (Eq. (1)). Income elasticity of water consumption can change for various reasons such as the change of lifestyle, preferences. Higher income elasticity along with the increase of per capita GDP leads to increases in the total water demand. With respect to the ecological quality indicators, the results show that after 2027 the objective of GES is not achievable with secondary treatment technology (Fig. 10). Additionally, in this case greater investments in wastewater infrastructure are required to treat the wastewater produced by the socioeconomic activities.

The assumption underlying this scenario is that there is water availability to cover the water demand as the main

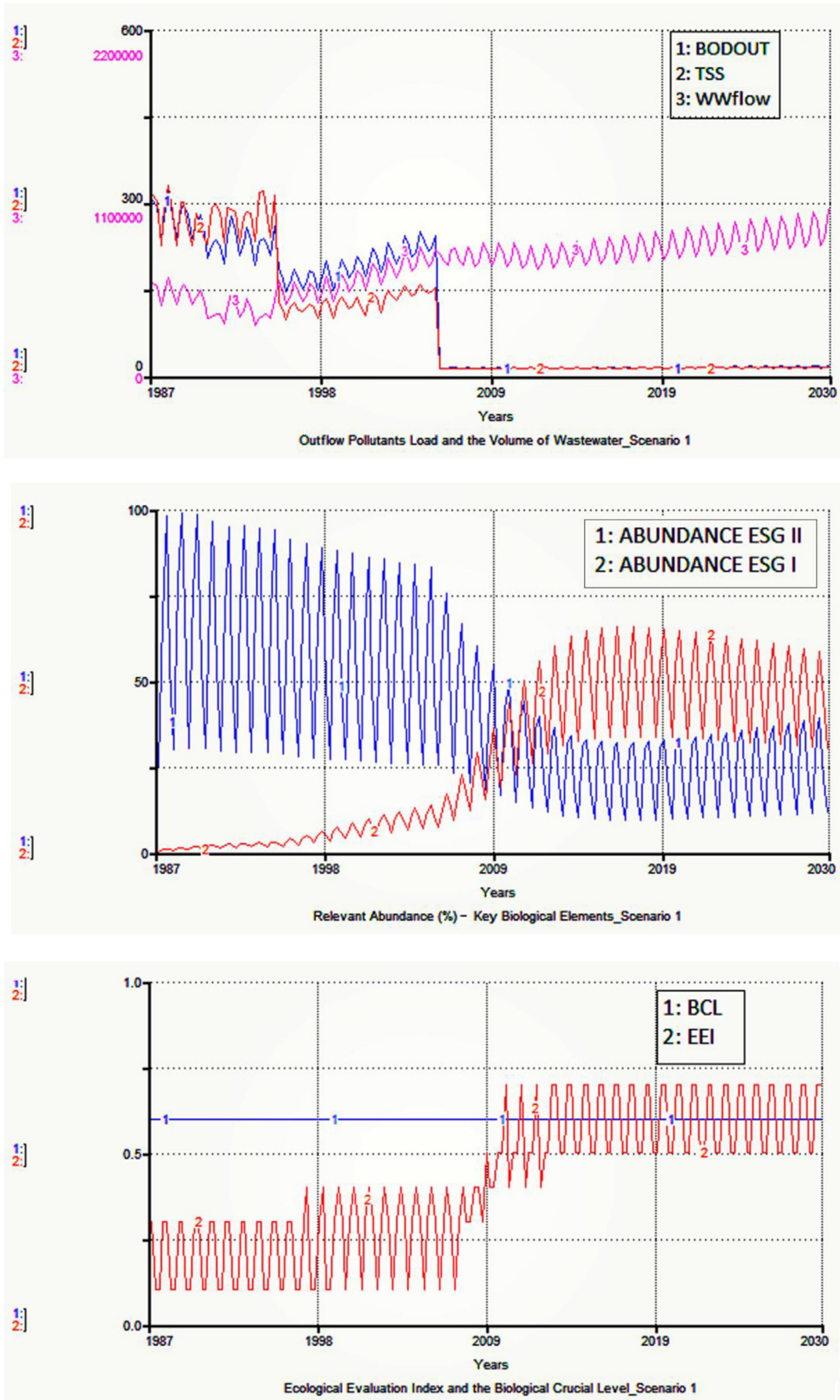

Fig. 7 – Simulation results for scenario 1 (baseline scenario). BODOUT = biological oxygen demand Outflow ((mg/l)/day), TSSOUT = total suspended solids outflow ((mg/l)/day), WWflow = volume of wastewater (m^3/day), BCL = Biological Crucial Level, EEI = ecological evaluation index. The numbers in the plots refer to different parameters.

objective of our study was to study water quality and not water quantity. In real world systems, however, even if technological advances can solve water quality issues, the availability of vital natural resources such as water or energy can create further constraints on socioeconomic activities. On the other hand, improving water quality may mitigate water quantity challenges. It has been proposed that "wastewater contains resources worthy of recovering and the development of technologies, practices, and policies that enable cost-effective recovery will have broad geopolitical implications" (Guest et al., 2009). For example, wastewater can be considered as a renewable resource where recovery of water, energy and materials is feasible through the current available technology (Guest et al., 2009).

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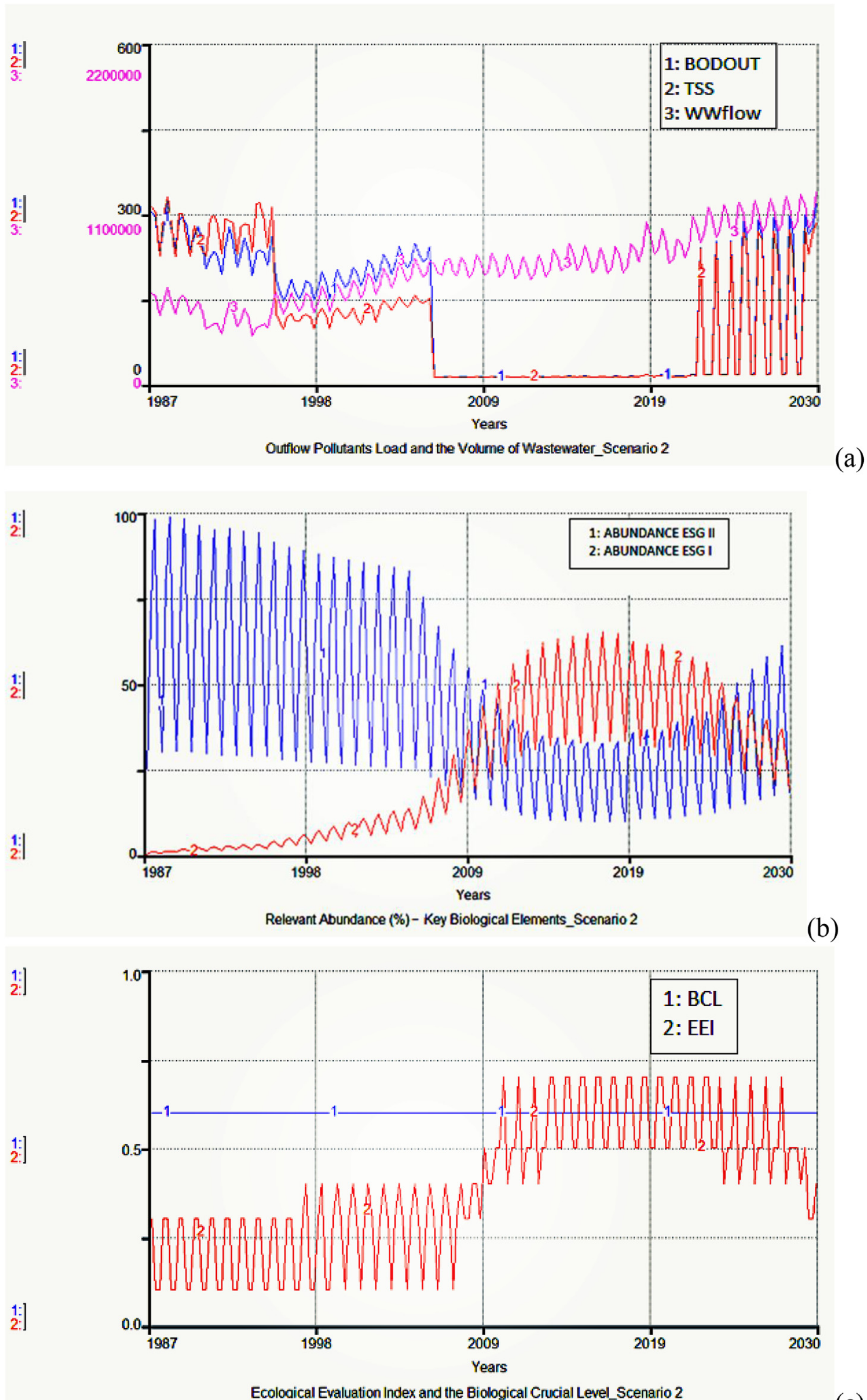

Fig. 8 – Simulation results for scenario 2 (combined sewer overflows scenario). BODOUT = biological oxygen demand Outflow ((mg/l)/day), TSSOUT = total suspended solids outflow ((mg/l)/day), WWflow = volume of wastewater (m^3/day), BCL = Biological Crucial Level, EEI = ecological evaluation index. The numbers in the plots refer to different parameters.

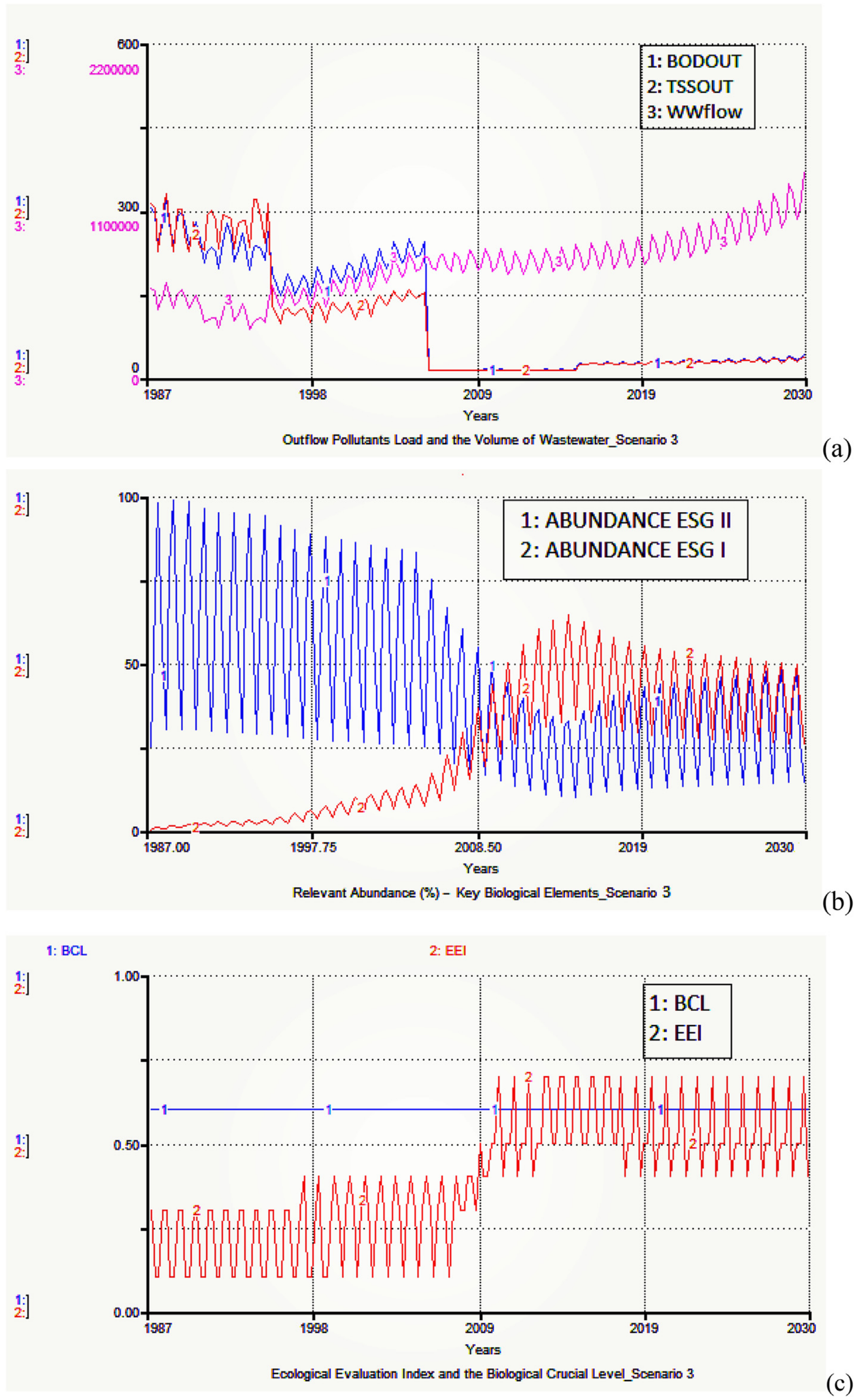

Fig. 9 – Simulation results for scenario 3 (Growth Scenario). BODOUT = biological oxygen demand Outflow ((mg/l)/day), TSSOUT = total suspended solids outflow ((mg/l)/day), WWflow = volume of wastewater (m^3/day), BCL = Biological Crucial Level, EEI = ecological evaluation index. The numbers in the plots refer to different parameters.

7. Conclusions

This paper presents a systems' thinking framework for studying the achievement of Ecologically Sustainable Development (ESD) in urban coastal systems. We combine elements from various disciplines (e.g. economics, biology, engineering) for the operational analysis of sustainability. Our analysis is unique in that we define ESD within an interdisciplinary framework of analysis resulting in the adoption of a measurable sustainability indicator. This indicator captures the response of key ecological functions and

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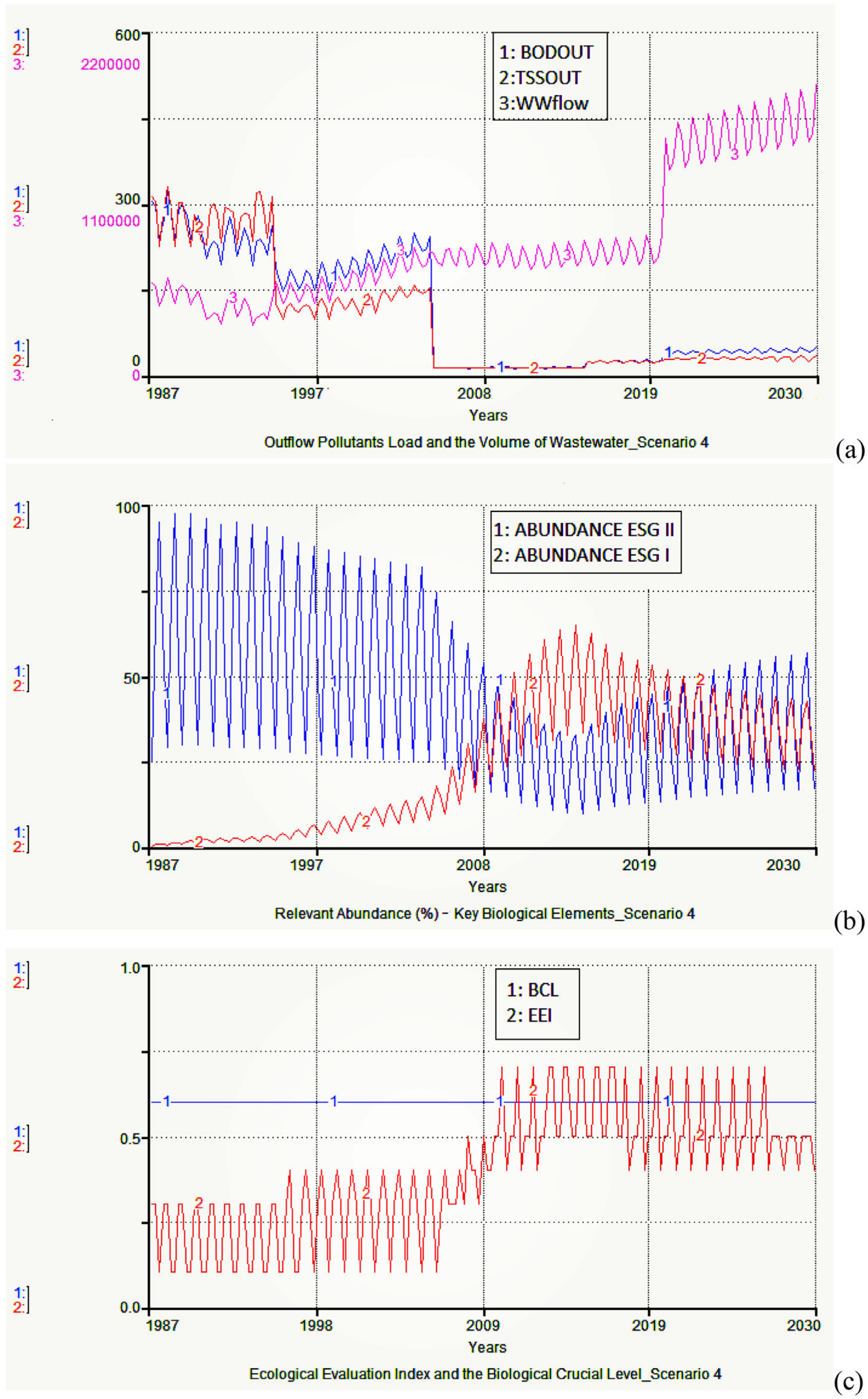

Fig. 10 – Simulation results for scenario 4 (increased water demand). BODOUT = biological oxygen demand Outflow ((mg/l)/day), TSSOUT = total suspended solids outflow ((mg/l)/day), WWflow = volume of wastewater (m^3/day), BCL = Biological Crucial Level, EEI = ecological evaluation index. The numbers in the plots refer to different parameters.

processes to anthropogenic stress and needs to be revised regularly to better incorporate new ecological findings. In addition, an institutional framework is necessary for enforcing sustainability at an operational level. Environmental policies define ecological targets and employ various policy instruments to regulate socioeconomic activities. Technology constitutes a key instrument for combating human impacts on the natural environment but using technology is subject to two main constraints: (i) the induced economic cost implied for the citizens in some cases is "unacceptably large" especially in developing countries that the per capita GDP is very low and; (ii) once the aggregate impacts exceeds certain levels, the technology may not be able to reduce the impact. In our case, the European policies for aquatic waters set the appropriate framework for managing the pollutant loads discharged into the urban coastal waters of Athens Metropolitan Area.

Our approach can trace the roots of the causes of change to key elements of the socioeconomic and ecological systems in order to inform decision makers in designing effective policies for attaining sustainability. Policy making is an endogenous parameter linked to sustainability targets if one defines the Good Ecological Status as the necessary condition for sustainability. Further research is needed (i) to better understand the complexity of decision making process and to improve this component in our approach; and (ii) to integrate water quantity aspects under alternative scenarios of climate change in the Mediterranean region.

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